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A German catalogue of archaeomagnetic data

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SUMMARY

A catalogue has been compiled of existing published and unpublished archaeomagnetic directional data from sites in Germany. The data comprise 125 results dated mainly in the past two millennia. The stability of the natural remanent magnetization was proven for most structures with at least a Thellier viscosity test, although for the majority of the data the direction is based on the characteristic remanent magnetization obtained from demagnetization experiments. Rock magnetic experiments carried out on the samples from many of the sites reveal that the dominant magnetic carrier is magnetite, often oxidized or with impurities. For many sites the archaeological age estimate is supported by physical dating methods. While the Roman epoch (0–400 AD) and the period from medieval to modern times (800–1700 AD) are reasonably well covered with data, the time interval in between and the first millennium BC are only poorly covered. The geographical distribution of data throughout Germany shows a concentration along the Rhine valley during Roman times, with in general a better coverage to the north. Nevertheless this data set clearly shows the secular variation during the past three millennia, and it extends the European archaeomagnetic data set considerably.

Key words: Archaeomagnetism, Germany, rock magnetism, secular variation.

INTRODUCTION

Direct observation of the total geomagnetic field vector started in many countries within the 19th century but the declination record can be traced back to the 16th century for some places where historical observations have been made. In order to extend the features of secular variation (SV) further back in time well-dated high-resolution sediments and historical lava flows can be used, but these are often not very precisely dated.

Archaeomagnetic data are another important source of information on the behaviour of the Earth's magnetic field during the last few millennia (Kovacheva 1997). The advantage of archaeological remains, such as ovens and fireplaces, is that dating based on archaeological and/or physical methods can be very precise. Additionally, in many places of the world archaeological sites for the past several millennia are abundant. These two points are crucial if one wants to reconstruct SV, because SV is a regional phenomenon. It is therefore necessary to have a good spatial and temporal coverage of the investigated region. In Germany, SV data from sediments exist for several places (Haverkamp & Beuker 1993; Schuch 1999; Stockhausen 1998; Werner *et al.* 1990), but few archaeomagnetic data have been published (see below). Nevertheless, many more measurements have been carried out but they are only documented in internal reports or unpublished diploma theses.

In order to make all these data available for analysis of the geomagnetic field, a compilation of all published and unpublished archaeodirections is presented here, including some archaeomagnetic measurements carried out in recent years in the palaeomagnetic laboratories in Grubenhagen, Cologne, Munich and Geneva.

REVIEW OF PUBLISHED DATA

According to the global archaeomagnetic database, the first palaeomagnetic measurements on German archaeological sites were carried out by Emile Thellier (Thellier 1981), who began work on archaeomagnetism in the late 1930s. All his sites in Germany lie close to the French border and consist mainly of pottery kilns. The 19 sites have ages between 30 and 1600 AD (Table 1, nos 1–19). The sampling and laboratory procedures have already been

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Table 1. Archaeomagnetic directions from German sites. Columns from left to right: structure number, structure name; age with 2σ error (^{14}C ages, according to the calibration curve INTCAL98, Stuiver *et al.* 1998) and method of dating (arch: archaeological age estimate, hist: historical document, C14: conventional ^{14}C dating, AMS: ^{14}C dating with the acceleration mass spectrometer technique, TL: thermoluminescence dating, strat.hm: stratigraphic constraints together with historical observations of the field direction), category after Tarling & Dobson (1995); number of samples (#: hierarchical mean was recalculated from original data, § : number of structures, *: number of specimens, see also text); declination, inclination, precision parameter and 95% confidence limit of characteristic remanent magnetization (ChRM), site name, kind of structure (n.r., not recorded), geographic latitude (°N) and longitude (°E), laboratory treatment (AF: alternating field demagnetization, Th: thermal demagnetization, Tv: Thellier viscosity test), determination of ChRM (step used for ChRM, or VT: NRM after viscosity test, lin: linear segment from the Zijderveld diagram, PCA: principal component analysis), rock magnetic experiments (A: anisotropy of susceptibility, C: determination of Curie temperature, H: hysteresis measurements, I: isothermal remanent magnetization acquisition), reference. Note that Tarling & Dobson (1995) recommend only the use of data with category 3 or better. The data can be requested from the first author as an Excel or ASCII file.

No.	Name	Age (yrs AD)	Method	C	N	D (°)	I (°)	k	α_{95} (°)	Site	Structure	Lat (°N)	Long (°E)	Treatment	ChRM	RM	Reference
Palaeomagnetic laboratory St. Maur, Institute of Geophysics, Paris																	
1	6	30 – 31	arch.	5	10	−1.7	68.7	333	2.4	Neuß/Umgehungsstrasse	n.r.	51.18	6.7	Tv	VT	-	Thellier, 1981
2	7.8	40 – 41	arch.	5	22	−11.3	68.5	122	2.7	Neuß	n.r.	51.18	6.7	Tv	VT	–	Thellier, 1981
3	21	280 – 330	arch.	5	14	−0.5	61.3	944	1.3	Trier/Speicher	n.r.	49.9	6.7	Tv	VT	–	Thellier (1981)
4	22	50 – 51	arch.	5	4	−2.5	65.7	2500	1.4	Asberg	n.r.	51.43	6.6	Tv	VT	–	Thellier (1981)
5	23	700 – 875	arch.	4	13	14.2	73.0	143	3.2	Walberberg	n.r.	50.78	6.9	Tv	VT	–	Thellier (1981)
6	24	40 – 41	arch.	5	11	−4.2	69.7	418	2.1	Neuß/Grünwegsiedlung	n.r.	51.18	6.7	Tv	VT	–	Thellier (1981)
7	33	50 – 70	arch.	5	8	−0.5	68.0	1270	1.5	Dormagen	n.r.	51.1	6.8	Tv	VT	–	Thellier (1981)
8	34	1550 – 1650	arch.	4	12	5.5	59.8	1571	1.0	Siegburg	n.r.	50.8	7.2	Tv	VT	–	Thellier (1981)
9	35	1250 – 1350	arch.	4	9	6.3	62.2	2370	1.0	Siegburg	n.r.	50.8	7.2	Tv	VT	–	Thellier (1981)
10	78	1150 – 1250	arch.	4	10	9.7	61.3	187	3.2	Forchtenberg	n.r.	49.3	9.5	Tv	VT	–	Thellier (1981)
11	79	1250 – 1275	arch.	5	8	10.8	58.9	584	2.0	Forchtenberg	n.r.	49.3	9.5	Tv	VT	–	Thellier (1981)
12	80	1200 – 1250	arch.	5	5	14.8	59.6	1294	1.8	Forchtenberg	n.r.	49.3	9.5	Tv	VT	–	Thellier (1981)
13	81	200 – 700	arch.	1	6	−2.1	70.6	467	2.6	Forchtenberg	n.r.	49.3	9.5	Tv	VT	–	Thellier (1981)
14	87	675 – 725	arch.	4	11	3	72.0	721	1.6	Forchtenberg	n.r.	49.3	9.5	Tv	VT	–	Thellier (1981)
15	90	175 – 200	arch.	5	7	3.5	61.3	2165	1.3	Xanten	n.r.	51.7	6.5	Tv	VT	–	Thellier (1981)
16	91	850 – 900	arch.	5	11	8.5	73.4	1057	1.3	Brühl-Eckdorf	n.r.	50.8	6.9	Tv	VT	–	Thellier (1981)
17	92	800 – 900	arch.	4	14	4.8	75.6	404	1.9	Brühl-Eckdorf	n.r.	50.8	6.9	Tv	VT	–	Thellier (1981)
18	103	280 – 281	arch.	5	8	0.2	63.4	487	2.2	Iversheim	n.r.	50.6	6.77	Tv	VT	–	Thellier (1981)
19	104	280 – 281	arch.	5	8	−3.8	62.7	1351	1.3	Iversheim	n.r.	50.6	6.77	Tv	VT	–	Thellier, 1981
Palaeomagnetic Laboratory Grubenhagen, GGA-Institute, Hannover																	
20	BD	1041 – 1042	hist.	5	3#	40.1	65.7	1685	3.0	Bremen/Dom	burnt clay floor	53.08	8.81	AF	VT	–	Pucher (1977)
21	FS	0 – 200	arch.	3	2#	5.6	68.3	113	–	Wolfenbüttel-Fümmelsee	fire places	52.15	10.42	AF	10mT	C	Pucher (1980a)
22	JK	800 – 1100	arch.	2	1#	25	68.0	–	–	Braunschweig/ Jacobikapelle	fire places	52.25	10.42	AF	20mT	C	Pucher (1980b)
23	MS	1100 – 1500	arch.	3	5#	16.7	65.1	55	–	Lübeck/Mengstrasse 62	bread oven	53.87	10.81	AF	20–0mT	C	Meyer *et al.* (1982)
24	DO	1200 – 1300	arch.	4	5#	−2.4	65.8	193	5.5	Dortmund	burnt clay floor	51.51	7.46	AF	10mT	–	Pucher & Fromm (1984)
25	EW11	1600 – 1700	arch.	3	2	−14	62.0	255	–	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
26	EW12	1600 – 1700	arch.	3	2	−1.3	64.1	46	–	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
27	EW21	1500 – 1600	arch.	4	3	9.4	68.7	498	5.5	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
28	EW22	1500 – 1600	arch.	4	3	−3.8	66.3	249	7.8	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
29	EW23	1500 – 1600	arch.	4	3	4.6	65.4	550	5.3	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
30	EW31	1400 – 1500	arch.	2	1	5.4	61.0	–	–	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
31	EW33	1400 – 1500	arch.	2	1	−7	60.9	–	–	Lübeck/Engelswisch	bread oven	53.87	10.81	AF	10mT	–	Fromm (1985)
32	D21	700 – 900	arch.	3	36	11.5	73.0	124	2.2	Düna	bread oven	51.68	10.27	AF	10mT	–	Fromm (1987)
33	D22	700 – 900	arch.	3	12	28.8	73.5	162	3.4	Düna	bread oven	51.68	10.27	AF	10mT	–	Fromm (1987)
34	D1	900 – 1100	arch.	3	12	26.5	65.9	817	1.5	Düna	bread oven	51.68	10.27	AF	10mT	–	Fromm (1986)
35	CG	1300 – 1430	arch.	4	3	0.8	62.3	1043	2.8	Coppengrave	pottery kilns	51.99	9.73	–	NRM	–	Fromm (1988)
36	B9	1210 – 1250	arch.	5	4#	12.3	59.9	5160	1.3	Bursfelde	glass furnace	51.54	9.64	AF	4mT	C	Kleinschmidt (1989)

Table 1. (*Continud.*)

No.	Name	Age (yrs AD)	Method	C	N	D (°)	I (°)	k	α_{95} (°)	Site	Structure	Lat (°N)	Long (°E)	Treatment	ChRM	RM	Reference
37	B15	1210 – 1250	arch.	5	6#	6	61.2	627	2.7	Bursfelde	glass furnace	51.54	9.64	AF	4mT	–	Kleinschmidt (1989)
38	ST	1210 – 1250	arch.	5	4#	7.8	60.3	685	3.5	Bursfelde	glass furnace	51.54	9.64	AF	4mT	–	Kleinschmidt (1989)
39	PL	1250 – 1480	arch.	3	2#	8.3	58.7	–	–	Eddigehausen/Burg-Plesse	open fire place	51.6	9.97	AF	5mT	–	Kleinschmidt (1989)
40	HF	1000 – 1100	arch.	4	15	11.3	67.4	646	1.9	Harsefeld	hearth	53.45	9.52	AF	15mT	–	Rolf (1990)
41	GO	893 – 1152	C14	3	2	13.6	63.8	213	–	Goslar/Bassgeige	fire place	51.94	10.42	AF, Th	lin.	CI	Schnepp (1996)
42	XA	100 – 300	arch.	3	5	−4.1	64.8	102	7.6	Xanten	fire places	51.68	6.45	AF, Th	lin.	CIH	Schnepp (1996)
43	WO	300 – 350	arch.	5	5	8	62.3	74	8.9	Worms	pottery kilns	49.64	8.36	AF, Th	lin.	CIH	Schnepp (1996)
44	BB	1320 – 1440	C14	5	5	5.1	64.4	499	3.4	Brandenburg	bread oven	52.42	12.55	AF, Th	PCA	CI	Schnepp & Pucher (1999)
45	BZ	1020 – 1190	C14	4	12	10.3	63.6	296	2.5	Belzig	pottery kiln	52.14	12.6	AF, Th	PCA	–	Biermans02
46	BS1	1200 – 1250	arch.	5	8	10.9	66.9	245	3.5	Braunschweig	hypocaust	52.27	10.52	AF, Th	PCA	–	Schnepp & Pucher (2000)
47	BS3	1290 – 1400	C14	5	18	7.5	64.9	141	2.9	Braunschweig	furnace	52.27	10.52	AF, Th	PCA	–	Schnepp & Pucher (2000)
48	BS4	1515 – 1565	arch.	5	35	7.8	67.8	112	2.3	Braunschweig	furnace	52.27	10.52	AF, Th	PCA	–	Schnepp & Pucher (2000)
49	L01	1580 – 1750	strat.hm	4	14	−16.2	73.8	596	1.6	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	–	Schnepp et al. (2003)
50	L02	1580 – 1750	strat.hm	4	9	−4.3	73.9	1712	1.2	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
51	L03	1580 – 1750	strat.hm	4	8	−7.9	76.3	2264	1.2	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
52	L04	1580 – 1750	strat.hm	4	9	−4.5	76.9	1570	1.3	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
53	L05	1580 – 1750	strat.hm	4	8	−5.5	76.1	580	2.3	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
54	L06	1580 – 1750	strat.hm	4	7	−1.9	75.1	1147	1.8	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
55	L07	1580 – 1750	strat.hm	4	9	−3.1	76.4	1211	1.5	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
56	L08	1580 – 1750	strat.hm	4	9	13.7	72.6	364	2.7	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
57	L09	1580 – 1750	strat.hm	4	6	12.2	71.7	332	3.7	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
58	L10	1580 – 1750	strat.hm	4	8	16	70.8	330	3.1	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
59	L11	1517 – 1740	TL	2	1	8.4	70.1	–	–	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
60	L12	1517 – 1709	TL	4	7	15	70.1	640	2.4	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
61	L13	1502 – 1709	strat.	3	4	12.8	71.1	1499	2.4	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
62	L14	1502 – 1654	TL	4	9	14.6	69.3	601	2.1	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
63	L15	1449 – 1654	strat.	3	9	15.1	68.3	560	2.2	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
64	L16	1449 – 1608	TL	3	8	8.1	69.6	239	3.6	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
65	L17	1448 – 1608	TL	4	8	3.6	68.2	224	3.7	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
66	L18	1448 – 1608	TL	4	8	10.6	67.0	1306	1.5	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
67	L19	1428 – 1549	TL	4	9	6.9	66.6	895	1.7	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
68	L20	1301 – 1549	strat.	3	10	3.9	65.3	356	2.6	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
69	L21	1301 – 1549	TL	3	7	7.7	63.5	519	2.7	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
70	L22	1301 – 1500	TL	3	8	3.4	64.5	163	4.4	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
71	L23	1301 – 1500	TL	3	11	5.6	64.4	926	1.5	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
72	L24	1283 – 1500	TL	3	8	9.5	63.6	446	2.6	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)
73	L25	1283 – 1378	TL/C14	5	8	14.2	65.9	146	4.6	Lübeck/Mühlenstr.	bread oven	53.87	10.81	AF, Th	PCA	CI	Schnepp et al. (2003)

Table 1. (*Continud.*)

No.	Name	Age (yrs AD)	Method	C	N	D (°)	I (°)	k	α_{95} (°)	Site	Structure	Lat (°N)	Long (°E)	Treatment	ChRM	RM	Reference
74	BL12	1290 – 1440	C14	4	20	4.9	60.2	177	2.5	Salzgitter/Burg-Lichtenberg	hypocaustic-heating	52.12	10.29	AF, Th	PCA	CIH	Schnepp (2002b)
75	SC13	1040 – 1390	C14	4	18	9.4	60.6	250	2.2	Schöningen/St.Lorenz	hypocaust	52.14	10.95	AF, Th	PCA	CIH	Schnepp 2002
76	SC2	1060 – 1400	C14	4	10	2.1	63.3	181	3.6	Schöningen/St.Lorenz	hypocaust	52.14	10.95	AF, Th	PCA	CI	Schnepp 2002
77	SC4	−200 – 700	C14	1	4	−5.4	60.2	510	4.1	Schöningen/St.Lorenz	hypocaust	52.14	10.95	AF, Th	PCA	CI	Schnepp 2002
78	NO1	1300 – 1450	C14	5	16	6.4	62.3	438	1.8	Nienover	hypocaust	51.68	9.52	AF, Th	PCA	CI	Schnepp 2002
79	SW	895 – 1020	C14/AMS	5	12	24.7	65.8	259	2.7	Schnapsweg	smelting-furnace	51.89	10.25	AF, Th	PCA	–	Schnepp 2002
80	FR	1261 – 1377	C14	4	17	2.8	59	262	2.2	Fredelsloh	pottery kiln	51.74	9.79	AF, Th	PCA	IH	Schnepp 2002
81	RT	1680 – 1930	C14	3	12	−3.8	64.8	341	2.4	Rosental	charcoal-pile	51.88	10.24	AF, Th	PCA	CI	Schnepp 2002
82	DD1	1300 – 1350	arch.	4	8	3.1	66.6	212	3.8	Dahmsdorf	lime furnace	52.3	13.27	AF, Th	PCA	–	this study
83	DD2	1045 – 1281	C14	5	9	18.5	61.8	403	2.6	Dahmsdorf	bread oven	52.3	13.27	AF, Th	PCA	I	this study
84	PW	−388 – −2	C14	3	18	−25.1	69.5	180	2.6	Pinnow	pottery kiln	53.07	14.07	AF, Th	PCA	I	this study
85	PH	−404 – −124	C14	4	10	−9.6	71.9	108	4.7	Phöben	pottery kiln	52.43	12.89	AF, Th	PCA	–	this study
86	SK12	−90 – 132	C14	4	13	−31.2	71.7	162	3.3	Satzkorn	pottery kilns	52.48	12.99	AF, Th	PCA	–	this study
87	SH	891 – 1015	C14	5	10	10.7	73.6	105	4.7	Stollhamm	hearth place	53.52	8.33	AF, Th	PCA	–	this study
88	AW	691 – 960	C14	4	6	17.2	67.7	384	3.4	Altenwalde	burnt castle-wall	53.83	8.66	AF, Th	PCA	–	this study
89	OH	300 – 400	arch.	4	9	7.5	71.3	170	4.0	Ohrum	fire place	52.13	10.56	AF, Th	PCA	–	this study
90	KM	−500 – −250	arch.	3	23	−19.5	65.2	31	5.5	Kallmünz	burnt castle wall	49.16	11.97	AF, Th	PCA	I	this study
91	KR1	−517 – −393	AMS	5	23	14	72	328	1.7	Krackow	burnt pit	53.35	14.27	AF, Th	PCA	–	this study
92	JW12	300 – 400	arch.	4	13	−11.3	68.5	119	3.8	Jänschwalde	lime furnaces	51.79	14.57	AF, Th	PCA	–	this study
Palaeomagnetic Laboratory, Section for Geophysics, Munich																	
93	MW	400 – 700	arch.	2	18	−3.5	71	1700	0.8	Mannheim	fire places	49.5	8.5	Tv	NRM		Schurr *et al.* (1984)
94	HC	1100 – 1200	arch.	5	8§	11.3	61.2	336	3.0	Herrenchiemsee	ovens	47.83	12.4	Tv	NRM	AC	Schurr *et al.* (1984)
95	PA	−3546 – −3497	dendro.	5	9#	−8.2	64	203	3.6	Pestenacker	hearth	48.03	10.54	AF	PCA	AC	Robeck (1991)
96	UN	−5100 – −4700	arch.	3	5#	8.9	55	1102	2.3	Untergaiching	oven	48.43	13	AF	PCA	CIH	Robeck (1991)
97	HC8	1100 – 1170	arch.	5	7§	14.3	60.2	1638	1.5	Herrenchiemsee	ovens	47.83	12.4	Tv, AF	NRM	CIH	Sirin (1992)
98	MM1	1150 – 1350	arch.	3	25*	11.4	63.6	350	1.5	Memmingen	oven	47.93	10.18	Tv	NRM	CIH	Sirin (1992)
99	MM2	1200 – 1400	arch.	3	74*	3.2	58.5	90	1.7	Memmingen	oven	47.93	10.18	Tv, AF	NRM	CIH	Sirin (1992)
100	HR1	584 – 804	TL	4	21*	−7.3	70.5	210	2.2	Herrching	lime furnace	47.99	11.16	Tv,Th	NRM	–	Becker et al. (1994)
101	KA	1350 – 1450	arch.	4	16*	8.3	52.7	286	2.4	Kempten	oven	47.44	10.19	Tv	NRM	–	Klee (1996)
102	KB	1350 – 1450	arch.	4	11*	6.3	53.4	1181	1.3	Kempten	oven	47.44	10.19	Tv	NRM	CI	Klee (1996)
Palaeomagnetic Laboratory, Geological Institute, Cologne																	
103	HA	−16 – 9	hist.	5	5	−4.2	66.8	5641	1.0	Haltern	oven	51.75	7.2	AF, Th	lin.	I	Reinders & Hambach (2001)
104	MF	100 – 200	arch.	4	10#	9.5	67.3	98	4.9	Mülfort	pottery kiln	51.2	6.3	Th	>530°C	CIA	Reinders & Hambach (1996)
105	P22	950 – 1050	arch.	4	3#	9.7	70.7	758	4.5	Pingsdorf	pottery kiln	50.83	6.9	AF, Th	lin.,35mT	CIA	Reinders *et al.* (1999)

Table 1. (*Continud.*)

No.	Name	Age (yrs AD)	Method	C	N	D (°)	I (°)	k	α_{95} (°)	Site	Structure	Lat (°N)	Long (°E)	Treatment	ChRM	RM	Reference
106	P23	1050 – 1130	arch.	3	2#	10.5	66.5	96	–	Pingsdorf	pottery kiln	50.83	6.9	AF, Th	lin.,35mT	CI	Reinders *et al.* (1999)
107	P26	1050 – 1130	arch.	5	3#	10.7	64.7	1271	3.5	Pingsdorf	pottery kiln	50.83	6.9	AF, Th	lin.,35mT	CI	Reinders *et al.* (1999)
108	P45	1130 – 1200	arch.	1	1#	13.7	63.5	–	–	Pingsdorf	pottery kiln	50.83	6.9	AF, Th	lin.,35mT	CI	Reinders *et al.* (1999)
109	LU	20 – 60	arch.	5	14	−7.6	65.7	274	2.4	Köln/Lungengasse	pottery kiln	50.94	6.97	AF, Th	PCA,35mT	CI	this study
110	LO	20 – 60	arch.	5	6	−9.1	66.7	485	3.1	Köln/Lungengasse	pottery kiln	50.94	6.97	AF, Th	PCA,35mT	I	this study
111	B234	656 – 690	C14	5	13	1.8	73.7	134	3.6	Bornheim/Walberberg	pottery kilns	50.77	7.01	AF, Th	PCA,35mT	I	this study
112	BA	0 – 100	arch.	2	1	−2.4	72.3	–	–	Bonn/Bastion	pottery kiln	50.74	7.1	AF, Th	PCA,35mT	–	this study
113	BB	0 – 100	arch.	4	7	−1.2	67.4	398	3.0	Bonn/Bastion	pottery kiln	50.74	7.1	AF, Th	PCA,35mT	I	this study
Petrophysical Laboratory, Mineralogy Department, Geneva University																	
114	EP	1300 – 1500	arch.	3	14	11.6	59	176	3.0	Esslingen/Predigerkloster	hypocaust	48.73	9.3	AF	25mT	I	Hedley unpu
115	BK	987 – 1187	arch.	3	13	15.4	59.3	102	4.1	Bebenhausen/Kloster	hypocaust	48.56	9.06	AF	8mT	–	Hedley unpu
116	QII	1400 – 1500	arch.	4	20	9.1	64.2	453	1.5	Bebenhausen/Schönbuch	glass furnace	48.58	9.04	AF	NRM	–	Hedley unpu
117	QIV	1400 – 1500	arch.	3	24	2.6	61.2	10	10.8	Bebenhausen/Schönbuch	glass furnace	48.58	9.04	AF	NRM	–	Hedley unpu
118	SV	900 – 1200	arch.	2	13	18.2	70.4	2106	0.9	Schwieberdingen/Vöhingen	hearth	48.88	9.12	AF	NRM	–	Hedley unpu
119	LT	1066 – 1096	dend.	5	14	29.2	63.3	93	4.1	Weil/Lachental	iron foundry?	48.62	9.03	AF	VT	–	Hedley unpu
Palaeomagnetic Laboratory, ETH, Zurich																	
120	AL11	16 – 496	TL	1	3§	5.4	57.6	29	23.2	Altliebel	iron-smelting slag	51.39	14.73	AF, Th	lin.	–	Koppelt *et al.* (2000)
121	LO3C	224 – 492	TL	2	3§	3.3	65.8	72	14.6	Lomske	slag	51.27	14.43	AF, Th	lin.	C	Koppelt *et al.* (2000)
122	RA9	−132 – 446	TL	1	1	−4.5	42.4	–	–	Rauden	slag	51.34	14.5	AF, Th	lin.	C	Koppelt *et al.* (2000)
123	SW3	255 – 487	TL	3	5§	−1.1	53.7	102	7.6	Spreewitz	slag	51.51	14.41	AF, Th	lin.	C	Koppelt *et al.* (2000)
124	WK8	−870 – −450	TL	1	2§	0	63.1	299	–	Weißkollm	slag	51.42	14.39	AF, Th	lin.	C	Koppelt *et al.* (2000)
125	ZW	−1800 – −800	arch.	0	1	6.8	62.2	–	–	Zwenkau	furnace	51.24	12.33	AF	lin.	CI	Wuytack (1998)

described in detail (Thellier 1981) and with slight modifications they have been adapted for all other studies reported here. Although not well known, the first activities in archaeomagnetism in Germany were started in the Grubenhagen palaeomagnetic laboratory, which belongs to the Leibniz Institute for Applied Geosciences (former NLfB—Geowissenschaftliche Gemeinschaftsaufgaben) by Pucher and Fromm during the late 1970s. Most data remained unpublished, with only a few results to be found in local archaeological journals (Fromm 1986; Meyer *et al.* 1982; Pucher 1977). During the 1990s these activities were continued by Schnepp, resulting mainly in brief reports in the archaeological literature (Biermann *et al.* 2001; Dussberg & Schnepp 2001; Schnepp 2002a; Schnepp & Pucher 1999, 2000), internal reports and one publication on a very exceptional sequence of 25 bread oven floors (Schnepp *et al.* 2003). During the 1980s palaeomagnetic work on archaeological sites also began at Munich University, and was reported in diploma theses and two publications (Becker *et al.* 1994; Schurr *et al.* 1984). Since 1992 data have also been collected at Cologne University (Reinders & Hambach 2001; Reinders *et al.* 1999) but these have not all been published. Furthermore, sites from southwestern Germany have been studied in Geneva since 1988 but they are only documented in internal reports. Finally, a few sites of iron production in the southeastern part of Germany have been investigated in a collaboration between Leipzig University and the Zurich palaeomagnetic laboratory (Koppelt *et al.* 2000).

METHODOLOGY

As outlined previously, the data presented here were collected over a research period of about 25 yr and measurements have been carried out in several laboratories using different instruments and measuring procedures, which furthermore evolved with time. Therefore demagnetization, for example, which is today a standard procedure for obtaining characteristic remanent magnetization (ChRM), was not always applied. On the other hand in all cases at least some demagnetization experiments or Thellier viscosity tests (Thellier & Thellier 1944) have been performed in order to verify stability of the natural remanent magnetization (NRM). From this point of view the data set is inhomogeneous, because demagnetization reduces the dispersion of the direction within an archaeological structure. On the other hand dispersion is much more strongly controlled by factors like the number of independent samples or the preservation and kind of structure itself. In the following, laboratory procedures are described separately for every laboratory.

Grubenhagen

In order to determine the ancient magnetic field direction for northern Germany by using archaeological finds such as kilns, ovens and furnaces, collaboration with archaeologists was started more than 25 yr ago (Pucher 1977). Because of the availability at that time of the astatic magnetometer, a palaeomagnetic instrument of high sensitivity, and applying the measuring techniques of Thellier (1981) large cubic samples were collected. However, for measurements in the laboratory, such as demagnetization experiments, they were cut into smaller cubes 30 or 16 mm in size. The sampling procedure itself depended on the mechanical properties of the archaeological structures and on the local site conditions. Generally a vertical column of baked clay was cut out and a horizontal or an inclined surface was established using a lump of plaster of Paris. The azimuthal orientation was measured with a magnetic compass, by a sun compass or by a theodolite. If necessary, the sample was encased in plaster. In the laboratory the samples were first consolidated by applying a silica gel before cutting the large samples into cubic specimens using a dry diamond circular saw. For the early investigations (see Table 1, nos 20–40) a standard laboratory procedure was applied to the material including measurement of the Curie temperature, bulk susceptibility, NRM and an alternating field (AF) demagnetization with only one step of 5 or 10 mT or several steps up to 80 mT. The demagnetization step with the lowest dispersion of the mean direction was then taken as the stable direction.

Since 1996 systematic archaeomagnetic studies (see Table 1, nos 41–92) have been started in order to establish an independent German secular variation curve. Since then sampling techniques and the palaeomagnetic measurements have been carried out in a more sophisticated manner. At least six independently oriented samples were taken from each archaeological structure (Table 1). In the case of baked clay or sand, the blocks (about $10 \times 10 \times 10$ cm) were wrapped with wet plaster bandages and on one side a plane smooth surface was prepared on the plaster. On this surface a strike and a dip line was drawn, then the dip was measured with an inclinometer and the azimuth was measured with a magnetic compass and whenever possible also with a sun compass. The difference between both measurements did not exceed $\pm 3^\circ$ and was not systematic. If the archaeological structure was constructed with hard materials such as bricks or stones, then samples were drilled and oriented, as is usual in palaeomagnetism studies, or a plane surface was made with plaster and oriented as described above, or a compass set on a triangular plate with three legs was used. In the laboratory unconsolidated hand samples were first impregnated with a product precipitating silica in the samples (RS-Steinfestiger) in order to consolidate it. Then cubes of 14, 20 or 24 mm in size were sawn (dry), whilst in the case of hard rocks they were either sawn (wet) into cubes or subsamples were drilled (wet) vertically to the orientation plane. In order to avoid polluting the magnetometers with dust or debris the surface of the cubes was covered with a water-soluble varnish (Kappaplex). Cores that were drilled in the field or that came from blocks were cut into standard cylindrical specimens 22 mm in length. Standard palaeomagnetic procedures were applied (as indicated in Table 1) including measurements of NRM and bulk susceptibility, calculation of the Koenigsberger ratio, a Thellier viscosity test and demagnetization with alternating field as well as thermally. Furthermore some rock magnetic work was carried out. Examples of these measurements will be discussed below.

Munich

Structures from seven sites in southern Germany, widely dispersed in time from the Mesolithic to the Middle Ages (see Table 1, nos 93–102), have been investigated in the Munich palaeomagnetic laboratory. Field work as well as laboratory studies essentially followed the recommendations of Thellier (1981) with modifications according to Becker (1978). Large hand samples were taken using the plaster technique and oriented with a theodolite or a sun compass. In one case some samples were also taken with a device that cuts out cylindrical samples, which were then put into plastic boxes. The unconsolidated large hand samples were cut (with a wet diamond circular saw) into cubic specimens of 6 cm edge length, again embedded in plaster. NRM was measured using a big sample fluxgate spinner magnetometer (Klee 1996) that was built by the laboratory, and the stability of the NRM was verified with Thellier viscosity tests. For most structures a few pilot specimens were subjected to AF or thermal demagnetization (see Table 1) and a single-component NRM could be demonstrated. For the mean ChRM direction only specimens with a viscosity index of less then 5 per cent were taken, and a structure mean for the specimens was calculated. For two sites (PA and UN, see Table 1) all specimens were AF demagnetized and the ChRM was obtained from principal component analysis (PCA) (Kirschvink 1980). The field and laboratory techniques employed were essentially the same as those published by Schurr *et al.* (1984).

Cologne

The Cologne laboratory worked on pottery kilns from six sites close to the Rhine valley (Table 1, nos 103–113). Two kilns were made from bricks or sandstone that served as oriented hand samples, while for the other kilns the Thellier technique as described above was used. Orientation was only possible with a magnetic compass. The block samples were reoriented in a sand box and drilled to give standard cores, while the baked clays were sawn (with a dry band saw) into cubes without further hardening, but the surface was covered with the water-soluble varnish (Kappaplex). Laboratory procedures were similar to those in Grubenhagen also including stepwise thermal and AF demagnetization and determination of the ChRM from the linear part of the Zijderveld diagrams or by PCA. In order to use all the specimens, for some structures the remaining specimens were subjected to one AF demagnetization step at 35 mT and this was also used for the ChRM direction.

Geneva

Samples from five sites in the surroundings of Stuttgart (Table 1, nos 114–119) were analysed by the Geneva laboratory. In these cases the English sampling technique (Clark *et al.* 1988) was used in which a 25 mm diameter plastic disc was glued on to the external surface of the baked clay and the orientation arrow was orientated using both magnetic and sun compasses and an electronic clinometer. Laboratory work was mainly restricted to determination of the NRM and a Thellier viscosity test. AF demagnetization with one step based on complete demagnetization of selected pilot specimens was applied to two structures. Nevertheless in all cases mean NRM directions are well confined and could be used for archaeomagnetic dating.

Leipzig/Zurich

In the Zurich palaeomagnetic laboratory mainly slag from iron smelting sites has been investigated (Table 1, nos 120–125). All these structures were sampled by removing the entire block of slag after giving it one orientation mark. In the laboratory cores were drilled from the slag blocks by the conventional technique (see above) and sawn into cylinders, while one block of unconsolidated baked clay (no. 125) was subsampled into plastic boxes. AF and thermal demagnetization, with evaluation of the linear segment, as well as determination of Curie temperature, was applied as standard laboratory procedure.

NEW RESULTS

For most of the structures summarized in Table 1 the procedures applied are documented in the corresponding reference. But in order to give a representative overview of the various structures and quality of the data the examples discussed below were chosen from the new structures as well as from those measurements documented elsewhere.

If large block samples are taken, then it is likely that not all of the small specimens cut out in the laboratory will contain sufficiently heated material. The Koenigsberger ratio (Q) is an appropriate parameter to distinguish well-heated specimens from those that were not sufficiently heated to carry a complete thermoremanent magnetization (TRM). Fig. 1 shows this for 24 structures representing the variability of the archaeological sites. NRM as well as magnetic susceptibility varies over many orders of magnitude, representing the various materials that were used in the construction of the ovens. The structures were divided into three groups: structures heated to low (e.g. hearths, fire places or burnt walls), moderate (ovens or hypocaustic heating systems) and high (kilns and furnaces) temperatures. Generally structures heated to very high temperatures have somewhat higher NRM intensities and bulk susceptibilities. Very low values come from limestones that were used to build the walls of hypocausts for example. This situation was also found for bricks, which gave the highest values (Fig. 1b), but here magnetic properties arise from the type of fabrication process at high temperatures and not from their use in a hypocaust.

In most cases there was a good correlation between high Koenigsberger ratios and well-grouped NRM directions, except for displaced bricks. In the case of high Koenigsberger ratios it was observed that demagnetization (both thermal and AF) treatment provided results that were easy to interpret and the ChRM was obtained using PCA. Fig. 2 shows examples of highly stable NRMs showing straight

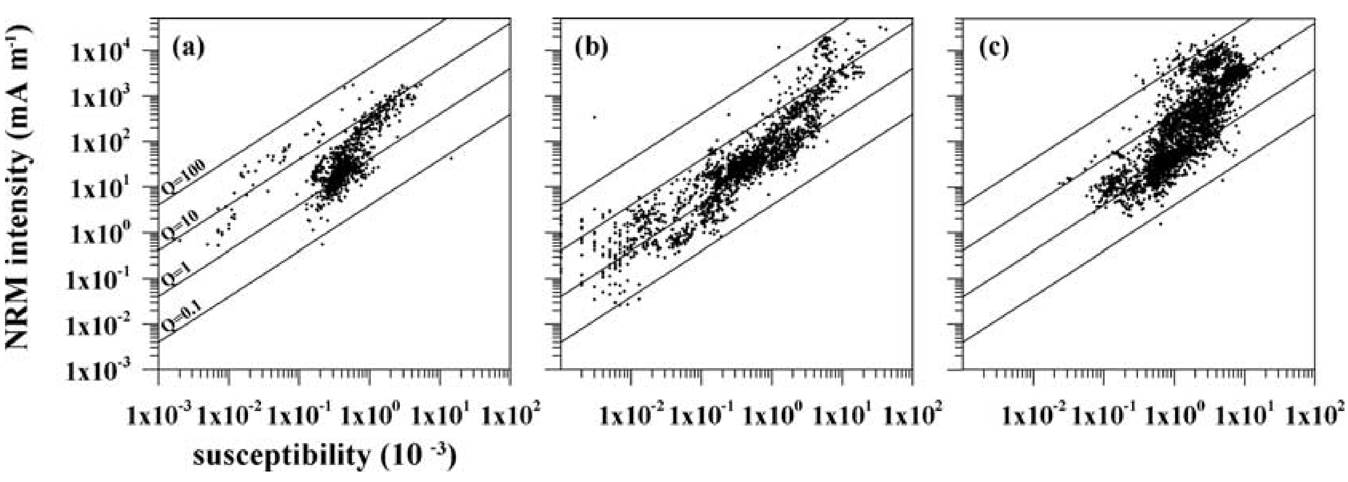

Figure 1. Intensity of natural remanent magnetization (NRM) plotted versus bulk susceptibility on a logarithmic scale for structures 44–48 and 74–92 of Table 1. Isolines of Koenigsberger ratios (Q) are shown: (a) hearths, fireplaces or burnt walls, (b) bread and other ovens, hypocausts, (c) pottery kilns and furnaces.

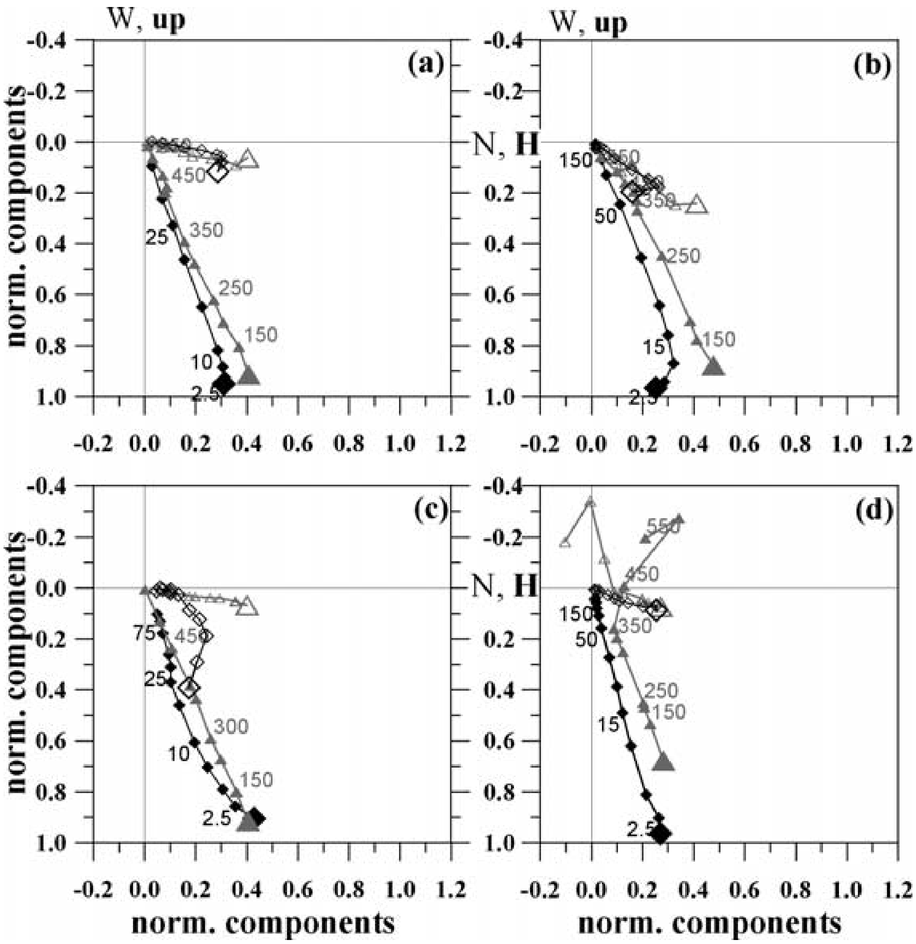

Figure 2. Demagnetization experiments (AF: black diamonds or dots, thermal: grey triangles) plotted in Zijderveld diagrams, solid symbols show the horizontal (Y, X), open symbols the vertical (Z, H) component, NRM is marked by a large symbol. Examples of various structures are shown (numbers refer to Table 1): (a) hearth no. 87, (b) burnt castle wall no. 88, (c) fire place no. 89, (d) burnt pit no. 91, (e) hypocaustic heating no. 76, (f) bread oven no. 83, (g) lime-furnace no. 92, (h) pottery kiln no. 84, (i) pottery kiln no. 86, (j) pottery kiln no. 111.

lines representing a TRM as well as unstable NRM consisting of a partial TRM due to the insufficient heating of the structure and a preserved primary magnetization of the material. In Figs 2(a–d) results of structures are shown, which were heated to relatively low temperatures. In all cases some viscous overprint is visible, but an obviously stable magnetization is observed. A strong change of magnetic properties during thermal demagnetization resulting in increasing susceptibility and intensity of magnetization is not systematically observed, but is seen in one case (Fig. 2d). Figs 2(e) and (f) are examples of moderately heated structures for which the demagnetization behaviour is not very different. The most scattered result (Fig. 2e) comes from thermal demagnetization of a limestone specimen, which has a very low remanence, but which also shows a stable magnetization direction, while the reheated brick resisted demagnetization with more than 50 per cent of the NRM intensity remaining after an AF field of 100 mT. The examples shown in Figs 2(g–j) belong to specimens from strongly heated structures. While the lime kiln (Fig. 2g) reveals the presence of some overprint during AF demagnetization, the pottery kilns (Figs 2h–j) have very stable magnetizations and weak viscous components that were easily removed. In all cases, ChRM directions obtained from both demagnetization methods agreed well within a structure. Generally, well-confined NRM directions for the structures are observed for specimens with Koenigsberger ratios of at least 2. In all cases viscosity tests or demagnetization experiments led to a better confinement of the mean direction.

ROCK MAGNETIC EXPERIMENTS

Thellier (1981) did not use rock magnetic experiments to determine the carriers of remanent magnetization and they were also not carried out systematically for all of the sites in Germany. Nevertheless, for many sites some information exists, which is representative of the various materials (see Table 1). For most of the sites studied in Grubenhagen, Cologne and Munich at least Curie point determinations or isothermal remanent magnetization (IRM) experiments have been performed. Fig. 3 shows the variability of thermomagnetic curves. For the baked clays (curves 1 and 2) as well as for other materials a Curie point between 550 and 600 °C is observed in most cases (Fig. 3b), indicating the presence of magnetite or a composition near magnetite, either containing impurities or that may have been slightly maghemitized. In most cases the thermomagnetic curves are relatively reversible, showing that the magnetic carriers are thermally stable. The heating curve often lies above the cooling curve, which means that the Curie point and the magnetization are lowered after heating to 700 °C. Another lower inflection point below 300 °C is sometimes observed for various materials: for samples

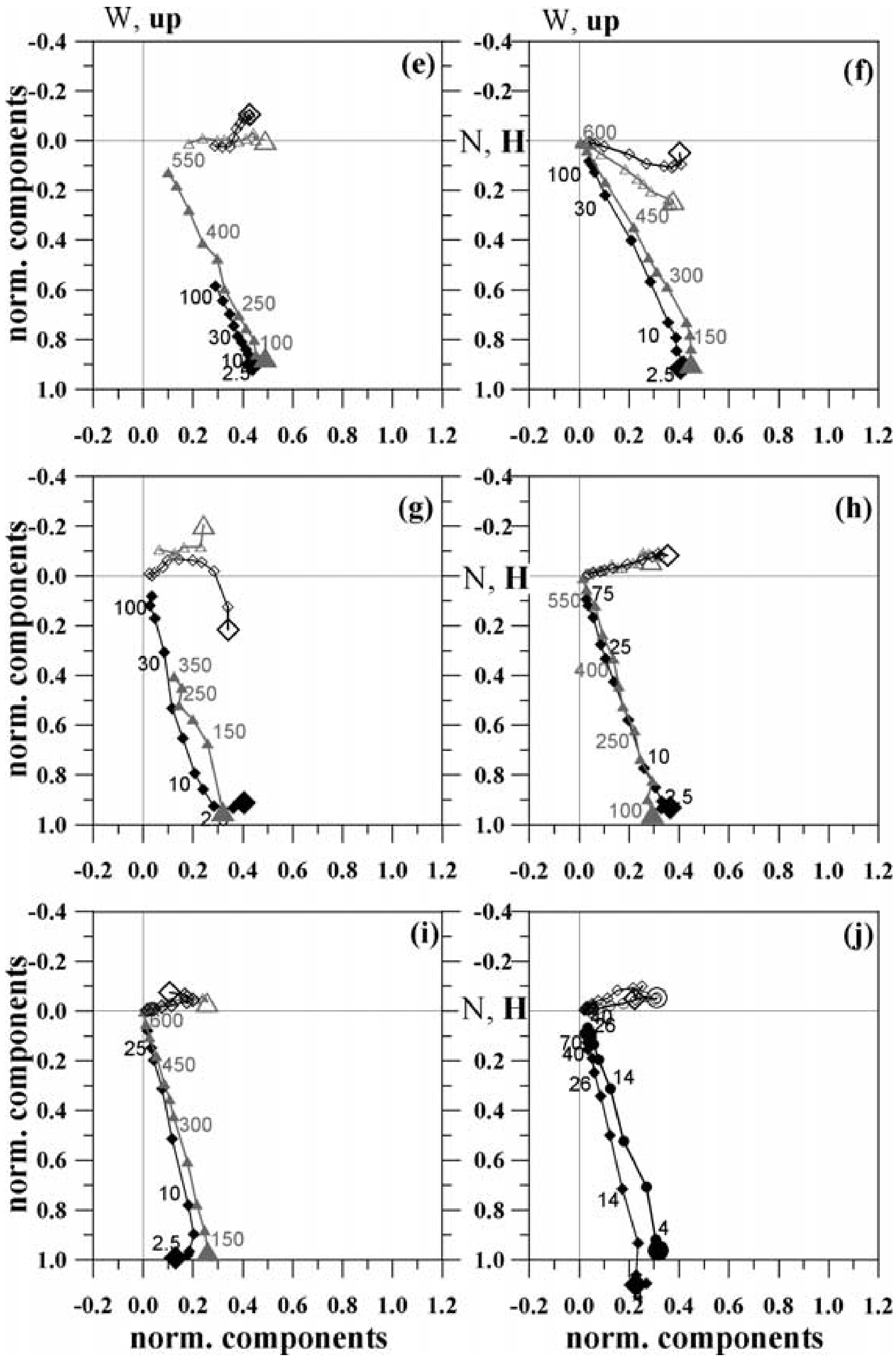

Figure 2. (*Continued*)

coming from the glassy part of pottery kilns (curve 3), for bricks (curve 4) or for baked clays sampled in very wet environments (i.e. Table 1, nos 95 and 96, Robeck 1991). This may be interpreted as the transformation from goethite or lepidocrocite to maghemite by dehydration during the thermomagnetic experiment. Very weak magnetic properties are observed for material such as limestones (curve 5) or greywackes (curve 6) that were used as building materials or that are present in the underlying natural horizon. Here as well a weak inflection is observed around 300 °C, which may also be due to the presence of pyrrhotite or other sulphur-bearing minerals. Although the baked material very often has a reddish colour that could be due to haematite, no clear indication of its presence could be obtained from thermomagnetic curves.

IRM acquisition curves (see Fig. 3c) show in most cases a saturation of at least 80 per cent at 300 mT, also pointing to a low-coercivity mineral, such as magnetite or maghemite, as the main magnetic carrier. Nevertheless in some samples from pottery kilns, bricks or limestone a mixture of low- and high-coercivity minerals is observed, showing that in rare cases the magnetization can be dominated by goethite or haematite.

In a very few cases hysteresis loops were also measured in order to get information on magnetic grain size (see Table 1, nos 49–64 and

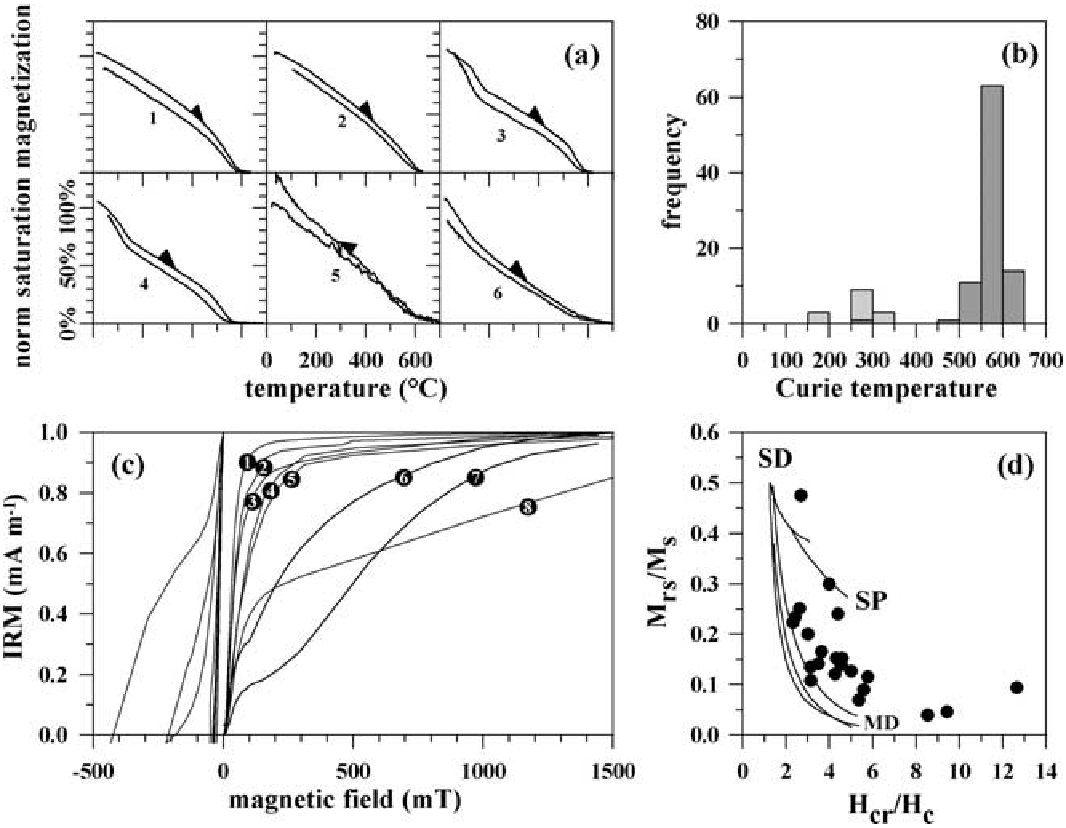

Figure 3. (a) Typical thermomagnetic curves from pottery kilns (1: no. 80; 2: no. 103; 3: no. 104), bricks (4: no. 74), limestone (5: no. 76) and greywacke (6: no. 81) b); distribution of Curie temperatures; c) typical isothermal remanent magnetization (IRM) acquisition and backfield curves of baked clays (1: no. 51; 2: no. 104; 3: no. 75; 4: no. 82; 5: no. 89), a brick (6: no. 76), glassy material from a pottery kiln (7: no. 104), and a limestone (8: no. 76); (e) Day diagram, lines are curves taken from Dunlop (2002) for mixtures of single-domain (SD) with multidomain (MD) or superparamagnetic (SP) magnetite particles.

96–99). The results are plotted in a Day diagram (Fig. 3d) together with single-domain (SD)/multidomain (MD) mixture curves taken from Dunlop (2002). The data from the present study plot in the same range as the pottery data shown therein. Therefore NRM properties are presumably often dominated by the stable SD grain fraction, but MD grains are also present in considerable amounts. Coercivity ratios above 5 together with low magnetization ratios may be due to a mixture of magnetite and haematite, the latter being present as a minor fraction in all samples. Here wasp-waisted hysteresis curves were observed.

THE DATA SET

Dating

For many databases of archaeomagnetic secular variation the timescale is based mainly on archaeological age estimates (Kovacheva 1997; Bucur 1994) and not on independent dating methods such as radiocarbon dating of charcoal, thermoluminescence (TL) dating of the fired material, or dendrochronology. The same is true for majority of the German archaeomagnetic data obtained before 1995 (Table 1). For most of the new data an alternative approach was made in order to get an independent date by using physical methods, which mainly supported the archaeological date estimate. For many of the structures reported here physical dating was undertaken principally using the radiocarbon method (^{14}C) on charcoal, by thermoluminescence (TL) of the baked clay, or by dendrochronology, e.g. with samples from the wooden housing in which the fireplace was found.

The charcoal samples have been dated with the conventional technique in the ^{14}C laboratory of the Leibniz Institute for Applied Geosciences (Hanover, Germany) by Dr M. Geyh or in the Leibniz Laboratory (Kiel, Germany) by Dr H. Erlenkeuser. Some were dated by Prof. P. Grootes using the acceleration mass spectrometry (AMS) technique, which is also a standard service of the Kiel Laboratory. Results so far unpublished are given in Table 2 and the calendar age with a 1σ or 2σ error margin (Table 1) was obtained by using a calibration program with the INTCAL98 data set (Stuiver *et al.* 1998). Table 2 allows the recalculation of the ages with other error margins or with a new calibration data set. If several age determinations were available, a weighted mean was calculated before the calibration was performed.

In two cases existing ^{14}C ages are not used in Table 1 [no. 82, *cf.* with Table 2, and no. 46, *cf.* with Schnepp & Pucher (2000)] because the archaeological age estimate in the entire context pointed reasonably to younger ages. As the ^{14}C method dates the time when the wood was growing and not when it was burnt in a fire, the age gives a lower limit and it can be considerably older (Aitken 1990). For some sites the archaeological dating was not taken from the reference given in Table 1 but from another archaeological reference that gives a more precise date (Table 1 nos 25–31: Gläser 1989; nos 109, 110: Carroll 2003; nos 120–124: Goedicke & Manzano 2000).

Table 2. List of recently sampled archaeological structures with archaeological age estimate according to the reference given: 1, Brauer (1999); 2, Eickhoff & Hahn-Weishaupt (1999); 3, Schwarzländer (1999); 4, Cziesla (2000); 5, Carroll (2003) or to personal communication (*) together with results of radiocarbon dating, if not given in a published reference. The first column is referring to structure numbers in Table 1.

No.	Structure	Archaeological age estimate	Method	Lab. no.	^{14}C age ($\pm 1\sigma$) (yr BP)	Dating δ^{13}C (PDB)	Age ($\pm 1\sigma$) (cal. AD)	Age ($\pm 2\sigma$) (cal. AD)
80	Fredelsloh FR	2nd half of 13th to 1st half of 14th AD *	con. ^{14}C	KI-5095,01	720 ± 30	−26.77	1277–1294	1261–1377
82	Dahmsdorf DD1	1st half 14th AD [1,*]	con. ^{14}C	Hv22859	915 ± 45	−25.7	1033–1206	1020–1221
83	Dahmsdorf DD2	mid to 2nd half 13th AD [1,*]	con. ^{14}C	Hv22860	830 ± 45	−25.5	1164–1262	1045–1281
84	Pinnow PW	Iron Age[2]	con. ^{14}C	KI-4478	2160 ± 65	−25.80	−356–107	−388–2
85	Phöben PH	Iron Age[3]	con. ^{14}C	KI-4477	2250 ± 65	−24.72	−395–203	−404–124
86	Satzkorn SK1	Iron Age[4]	con. ^{14}C	––	––	––	––	––
86	Satzkorn SK2	Iron Age[4]	con. ^{14}C	Hv23238	1965 ± 55	−25.4	−38–116	−90–132
87	Stollhamm SH	14th AD *	AMS ^{14}C	KIA1252	1095 ± 25	−26.29	898–984	891–1015
88	Altenwalde AW	late 9th–late 10th AD *	con. ^{14}C	KI-4808,02	1240 ± 40	−27.62	776–890	691–960
89	Ohrum OH	4th AD *	con. ^{14}C	KIA14404	1970 ± 30	−25.50	−15–71	−41–120
90	Kallmünz KM	5th BC–8th AD *	TL		No charcoal found; no quartz or feldspar for TL found			
91	Krackow KR1	Iron Age, BC *	con. ^{14}C	KIA12350	2375 ± 30	−27.69	−517–399	−434–393
111	Bornheim B2	7th AD[5]	con. ^{14}C	KJ-4406	1480 ± 30	−27.00	660–682	656–690
111	Bornheim B3	7th AD[5]	con. ^{14}C	KI-4404	1210 ± 30	−27.65		
111	Bornheim B4	7th AD[5]	con. ^{14}C	KI-4405	1350 ± 30	−26.68		

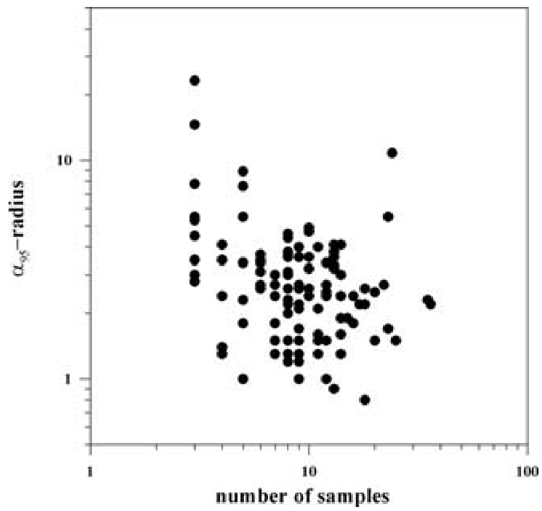

Figure 4. α_{95} values of the ChRM directions (Table 1, $N = 3$) plotted versus number of investigated samples per structure.

ARCHAEOMAGNETIC DIRECTIONS

In order to have uniformity between all the data, they have been re-examined taking into account the recommendations of Lanos *et al.* (2003) concerning specimen, sample and structure levels. The worst technique is to take only one large sample with a single orientation mark and to subsample it in the laboratory to produce many specimens, because any orientation error becomes systematic. Koppelt *et al.* (2000) used this technique for iron-smelting slag and here location means have been recalculated from the data, where the dating by Goedicke & Manzano (2000) was also given for the entire location. It is obvious that if the structure mean is calculated from many specimens, which are subsamples taken from a few independently oriented samples, the α_{95} is strongly underestimated and the mean is biased by those samples having the largest number of specimens. Averaging only over specimens was done in some of the unpublished reports as well as for published data (*cf.* Table 1, column N marked by *, # or §). In some cases (#), it was possible to retrieve the original data and the structure mean was recalculated hierarchically respecting specimen and sample levels (Lanos *et al*. 2003). In those cases where this was impossible, but structure means were given and were considered to have the same age, a site mean was recalculated from the structure means (§). Table 1 has a structure similar to that of the archaeomagnetic database managed by Tarling (http://www.ngdc.noaa.gov/seg/potfld/paleo.shtml). Additionally, the kind of the structure and the kind of rock magnetic experiments performed for the samples is listed. Following Tarling & Dobson (1995) a quality category was also assigned, paying most attention to the precision of the age dating. Category 0 to 2 occurs in 15 cases: in nine cases because of imprecise dating (Table 1: 13, 22, 77, 93, 118, 120, 122, 124, 125) and in six cases because only one large block sample was investigated.

Fig. 4 shows the 95 per cent confidence limit of the mean directions plotted versus the number of samples. The distribution is dominated by results which are based on at least six independent samples and α_{95} less than 4°. Compared with the cut-off limit of 1.5° proposed by Thellier (1981) most of the results have a large dispersion. On the other hand the results of only two structures exceed the limit of 9° given by Tarling & Dobson (1995). Furthermore Lanos *et al.* (2003) demonstrated that a cut-off is not justified, if the averaging procedure of the curve takes the error in time and direction into account. Therefore only data with a very imprecise time estimate or without directional error (because $N < 3$) should be avoided to determine a secular variation curve. Accordingly 15 out of 125 archaeodirections should not be used for such a reference curve.

Fig. 5 shows the spatial distribution of the data over Germany. Dots correspond to the sites listed in Table 1 and if a site provided several structures and independent archaeodirections this is indicated by a circle surrounding a cross. It can be seen that the spatial distribution is very uneven and most of the sites are concentrated along the Rhine valley close to Cologne, south of Hanover, and in the north at Lübeck.

The temporal distribution of the German archaeodirections is shown in Fig. 6 as a histogram as well as plots of declination and inclination versus time. The temporal distribution is strongly biased towards medieval and modern times and three or more archaeodirections per century are available since the 7th century AD. Compared with the databases available for France or England (Daly & Le Goff 1996) the German database is so far rather poorer. For this reason no average curve will be presented here because improvement of the database is still needed. However, even without the calculation of a smoothed curve, the secular variation can clearly be seen in Figs 6(a) and (b). Compared with the new secular variation curve recently presented for France (Gallet *et al.* 2002) the same main features of swings of declination and inclination are seen. On the other hand it seems there are time intervals with a very high dispersion of the inclination data for example in the first centuries AD and late medieval times (12th to 15th centuries).

In some of these cases the age determination may be questionable, as for site 92 (*cf.* Table 1) where archaeologists do not exclude the first half of the first millennium BC, but all archaeological evidence points to the given younger age interval, or for site 89, where a large discrepancy between archaeological and physical age determination occurs. Site 86 lies far away from all the other sites forming the cluster in the first centuries AD and perhaps shows already that secular variation showed higher inclinations in the northeastern part

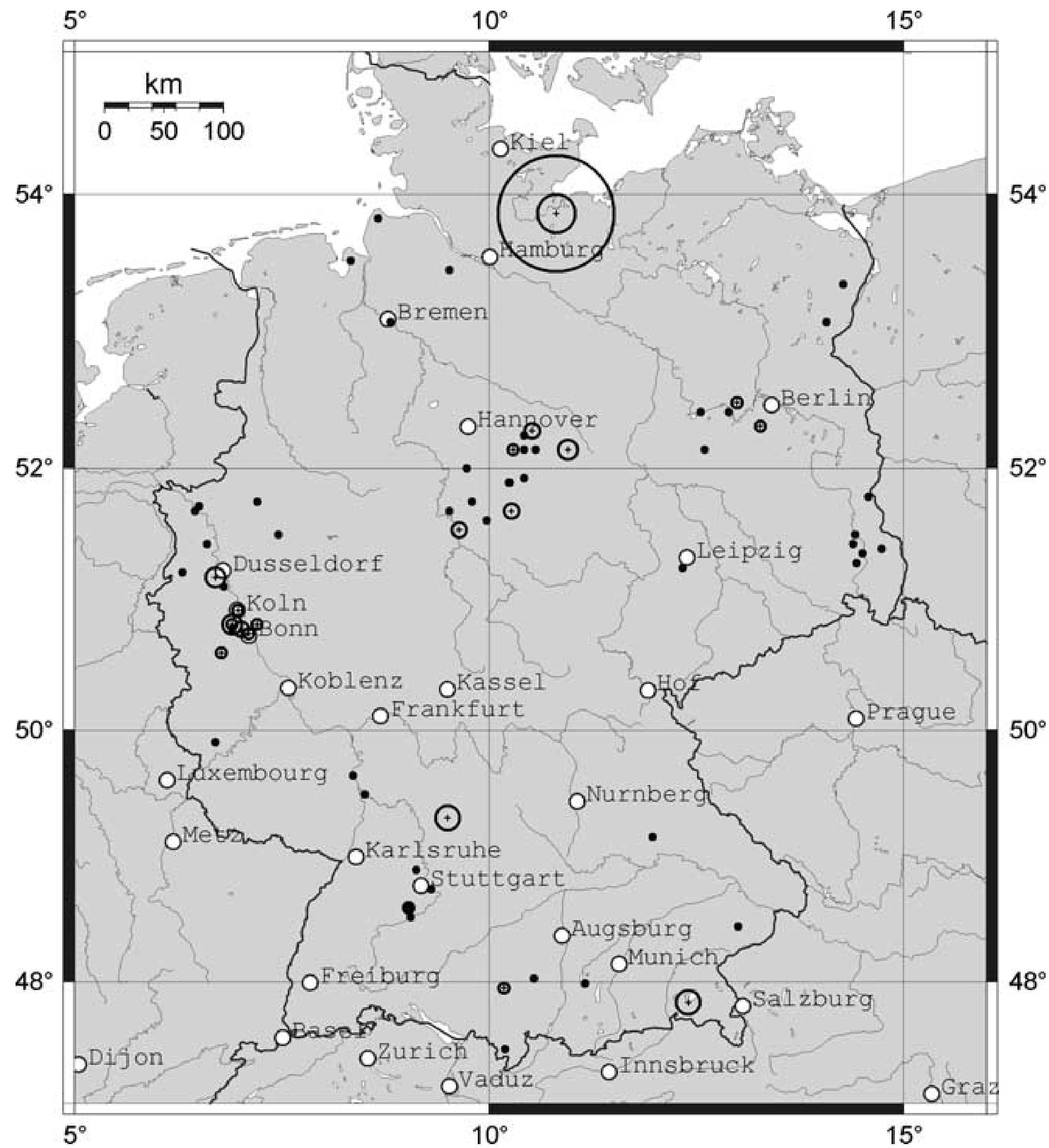

Figure 5. Map showing locations of archaeomagnetic sites. A dot represents one archaeological structure at a site, whilst its size corresponds to the number of structures investigated at the same site (between 2 and 25, *cf.* Table 1).

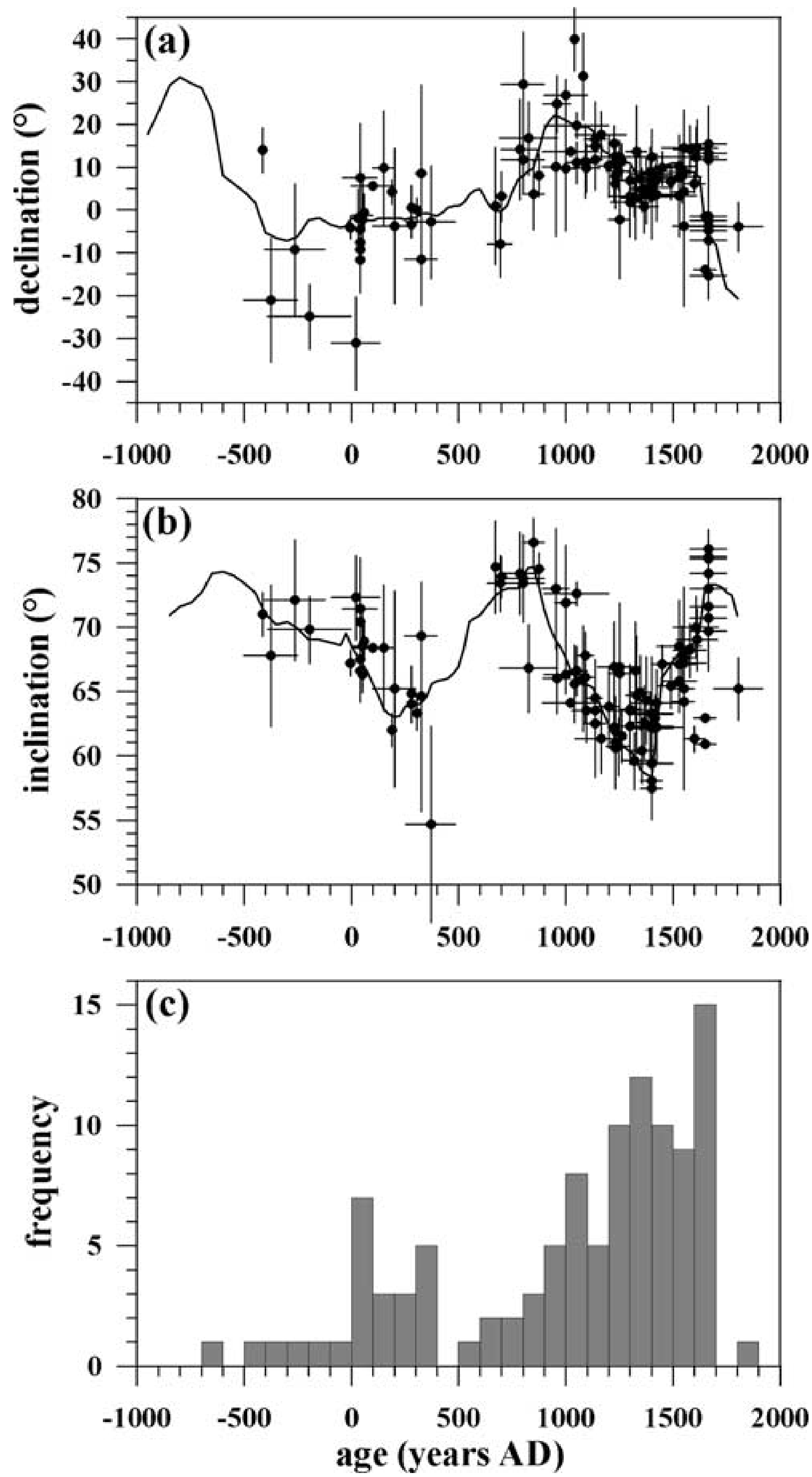

Figure 6. Declination (a) and inclination (b) values plotted versus age together with error bars (2σ or archaeological estimate for age, 95 per cent confidence limit for direction, only data with $C \geq 3$, recommended by Tarling & Dobson, 1995) and the French secular variation curves (Gallet *et al.* 2002). (c) Age distribution of the investigated structures.

of the investigated area (*cf.* Fig. 5). The same may be seen in the time interval 1200 to 1500 AD where the French curve shows a pronounced minimum in inclination. At least six sites show much steeper inclinations (24, 46, 47, 73, 82, 98) and four of them lie in the northeastern part of Germany.

Another explanation for such a strong dispersion could be a disturbance by TRM anisotropy or magnetic refraction. A TRM anisotropy, as in pottery (Chauvin *et al.* 2000) may occur in structures in which smoothed layers of clay were applied in the inner part of the oven, while refraction (see e.g. Soffel & Schurr 1990) would be expected for strongly magnetic structures. In both cases it would lead to a shallowing of inclination in the floor of the structure. Accordingly this should be seen for example in pottery kilns, which have a smoothed inside made of clay and show strong magnetizations (*cf.* Fig. 1). Although some of the pottery kilns investigated (109, 110 or 80) show low inclinations compared with other sites this is not systematic. It seems that the dispersion arises from the various error sources discussed by Lanos *et al.* (2003).

CONCLUSION

This paper presents a collection of 125 archaeomagnetic directions obtained from archaeological burnt structures in Germany. The majority of these sites are dated to the past two millennia. Whilst the Roman period (0–400 AD) as well as medieval to modern times (800–1700 AD) are covered with a reasonable number of data, the time interval in-between is only poorly covered, as is the first millennium BC. The spatial distribution throughout Germany shows a concentration along the Rhine valley in Roman times, and generally has a better coverage in the northern part. Nevertheless this data set does not seem sufficient for the elaboration of the first archaeomagnetic secular variation curve for Germany.

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